

Compressed Spectrum at the LHC

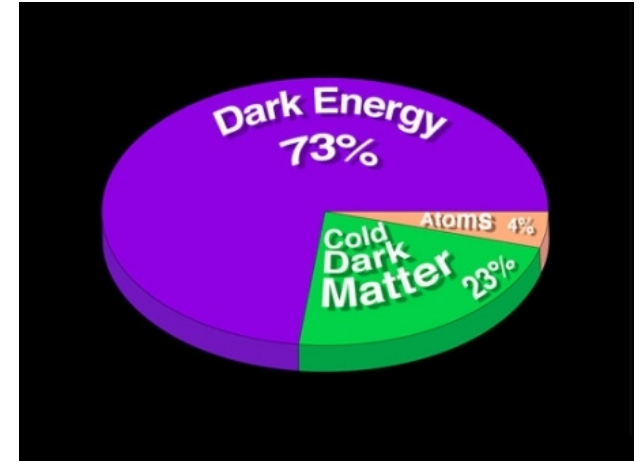
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Texas A&M University

**LHC After the Higgs
Santa Fe, 2014**

Big Picture

→ We want to understand the next layer of matter at the LHC - Dark Matter



→ DM content determination mostly depend on colorless particles, e.g., sleptons, staus, charginos, neutralinos, etc. and also depend on small mass gaps (ΔM) between lightest (LSP) and next to lightest particles (NLSP)

→ How do we produce these non-colored particles and the DM particle at the LHC? Can we understand the origin of DM?

Dark Matter: Thermal

Production of thermal non-relativistic DM:



Non-relativistic

Freeze-Out: Hubble expansion dominates over the interaction rate

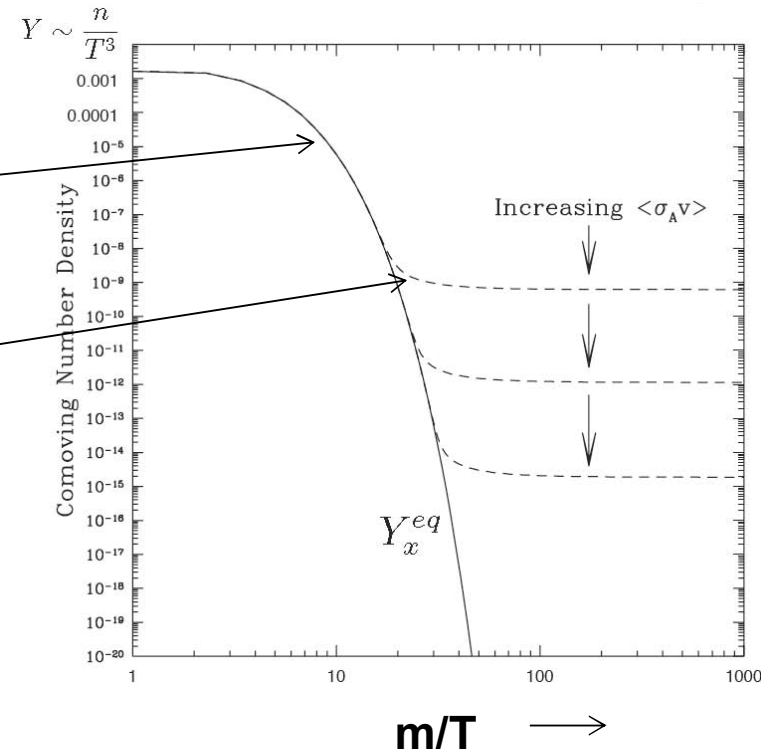
Dark Matter content: $\Omega_{DM} \sim \frac{1}{\langle \sigma v \rangle}$

freeze out $\rightarrow T_f \sim \frac{m_{DM}}{20}$

$$\rightarrow \langle \sigma v \rangle = 3 \times 10^{-26} \frac{cm^3}{s}$$

Assuming : $\langle \sigma v \rangle_f \sim \frac{\alpha_\chi^2}{m_\chi^2}$

$\alpha_\chi \sim O(10^{-2})$ with $m_\chi \sim O(100)$ GeV leads to the correct relic abundance



Dark Matter: Thermal

Suitable DM Candidate:

Weakly Interacting Massive Particle (WIMP)

Typical in Physics beyond the SM (LSP, LKP, ...)

Most Common: Neutralino (SUSY Models)

smaller annihilation
cross-section



Neutralino: Mixture of Wino, Higgsino and Bino

Larger annihilation
cross-section, smaller mass gaps

Wino, Higgsino → smaller ΔM is inevitable between NLSP & LSP

Bino → May require smaller ΔM between NLSP & LSP for thermal DM

Can we establish these features at the LHC?

Dark Matter: Non-Thermal

$\langle \sigma_{ann} v \rangle$: different from thermal average, $\Omega_{DM} \sim \frac{1}{\langle \sigma v \rangle}$ is not 26%
Non-thermal DM can be a solution

DM from the decay of heavy scalar field, e.g., Moduli decay

[Moduli : heavy scalar fields gravitationally coupled to matter]

Decay of moduli/heavy field occurs at:

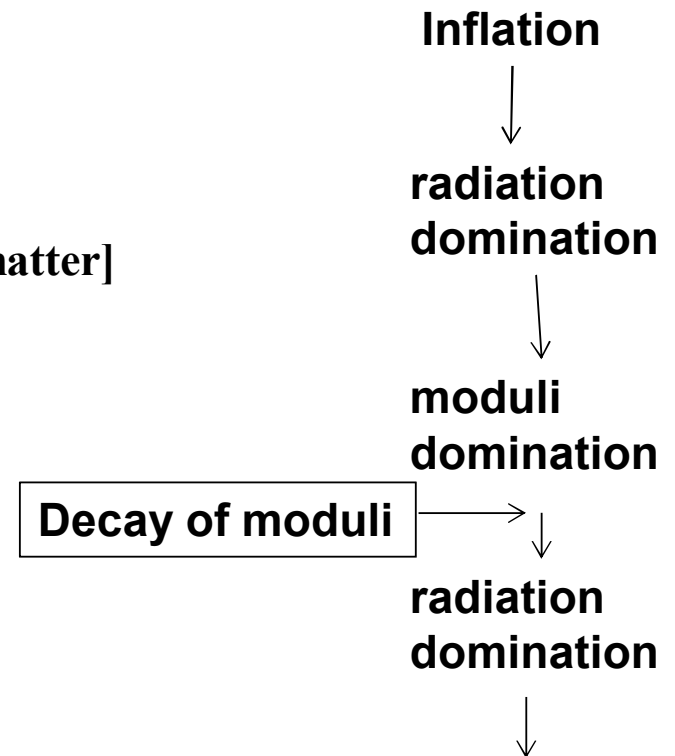
$$T_r \sim c^{1/2} \left(\frac{m_\phi}{100 \text{ TeV}} \right)^{3/2} (5 \text{ MeV})$$

$T_r \sim \text{MeV}$: Not allowed by BBN

For $T_r < T_f$: Non-thermal dark matter

Abundance of decay products $Y_\phi \equiv \frac{3 T_r}{4 m_\phi}$

DM content: also need to consider the DM annihilation.



Dark Matter: Non-thermal

➤ For $T_r < T_f$, larger annihilation cross-section $\langle \sigma_{ann} v \rangle_f = \langle \sigma_{ann} v \rangle_f^{th} \frac{T_f}{T_r}$ is needed for $\Omega \rightarrow 26\%$

➤ For $T_r \ll T_f$, Yield $Y_\phi \equiv \frac{3 T_r}{4 m_\phi}$ is small enough (10^{-10})
DM will be produced without any need of annihilation
[Note: For $m_{DM} \sim 10$ GeV, Y_ϕ is needed to be $\sim 10^{-10}$ to satisfy the DM content]

Outcome:

- Large (Wino/Higgsino) and small annihilation (Bino) cross-section from models are okay
- We may not need any annihilation

Since $\phi \rightarrow DM + \text{other particles}$, abundance (for $T_r \ll T_f$): 10^{-10}

➤ The Baryon and the DM abundance are correlated $\sim 10^{-10}$

Barrow, '82; Kamionkowski, Turner, '90; Gelmini, Gondolo, Soldatenko, Yaguna, '07
Allahverdi, Dutta, Sinha, '09, '10, '11, '12, '13; Acharya, Kane, Kumar, Watson, '09, '10 6

Thermal, Non-thermal

➤ **LHC: Measurement of DM annihilation cross-section, smaller ΔM is crucial**

**$\langle \sigma_{ann} v \rangle$: Large \rightarrow multicomponent/non-thermal;
Small \rightarrow Non-thermal**

➤ **DM annihilation from galaxy, extragalactic sources:**

Annihilation into photons: Fermi, H.E.S.S.

Annihilation into neutrinos: IceCube

Annihilation into electron-positrons: AMS

Small DM effects in the annihilation cross-section are absent in the data from the present epoch

LHC status...

→ Recent Higgs search results from Atlas and CMS indicate that $m_h \sim 126$ GeV

• in the tight MSSM window < 135 GeV

→ $m_{\tilde{q}} \text{ (1st gen.)} \sim m_{\tilde{g}} \geq 1.7$ TeV

→ For heavy $m_{\tilde{q}}$, $m_{\tilde{g}} \geq 1.3$ TeV

→ \tilde{t}_1 produced from \tilde{g} , $m_{\tilde{t}_1} \geq 700$ GeV

→ \tilde{t}_1 produced directly, $m_{\tilde{t}_1} \geq 660$ GeV (special case)

→ $\tilde{e} / \tilde{\mu}$ excluded between 110 and 280 GeV for a mass-less $\tilde{\chi}_1^0$ or for a mass difference > 100 GeV, small ΔM is associated with small missing energy

→ $\tilde{\chi}_1^\pm$ masses between 100 and 600 GeV are excluded for mass-less $\tilde{\chi}_1^0$ for $\tilde{\chi}_1^\pm$ or for the mass difference > 40 GeV decaying into e/μ

LHC Constraints and DM

LHC constraints on first generation squark mass + Higgs mass:

**Natural SUSY and dark matter [Baer, Barger, Huang, Mickelson, Mustafayev and Tata'12; Gogoladze, Nasir, Shafi'12, Hall, Pinner, Ruderman,'11; Papucchi, Ruderman, Weiler'11],
Higgs mass 125 GeV & Cosmological gravitino solution
[Allahverdi, Dutta, Sinha'12]**

→ Higgsino dark matter

Higgsino dark matter has larger annihilation cross-section

Typically $> 3 \times 10^{-26} \text{cm}^3/\text{sec}$ for sub-TeV mass

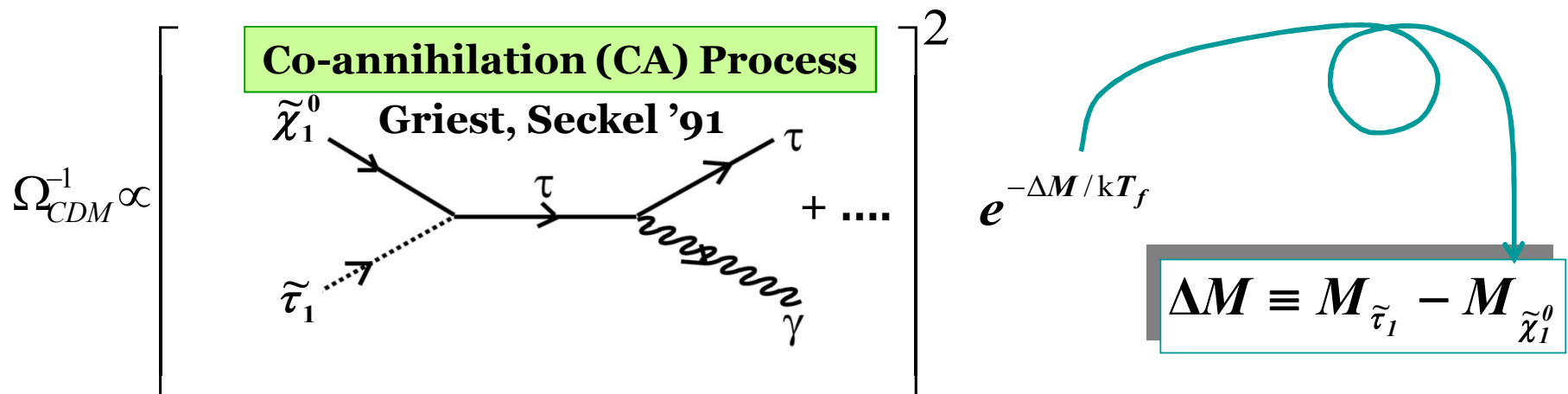
→ Thermal underproduction of sub-TeV Higgsino

Higgsino DM has small ΔM

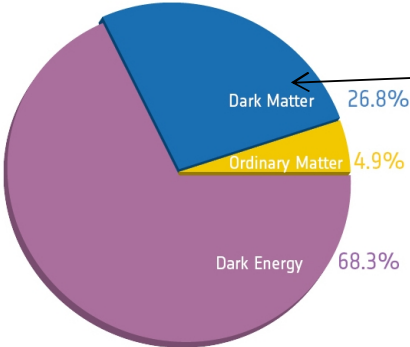
→ Can we establish this scenario at the LHC?

Small ΔM

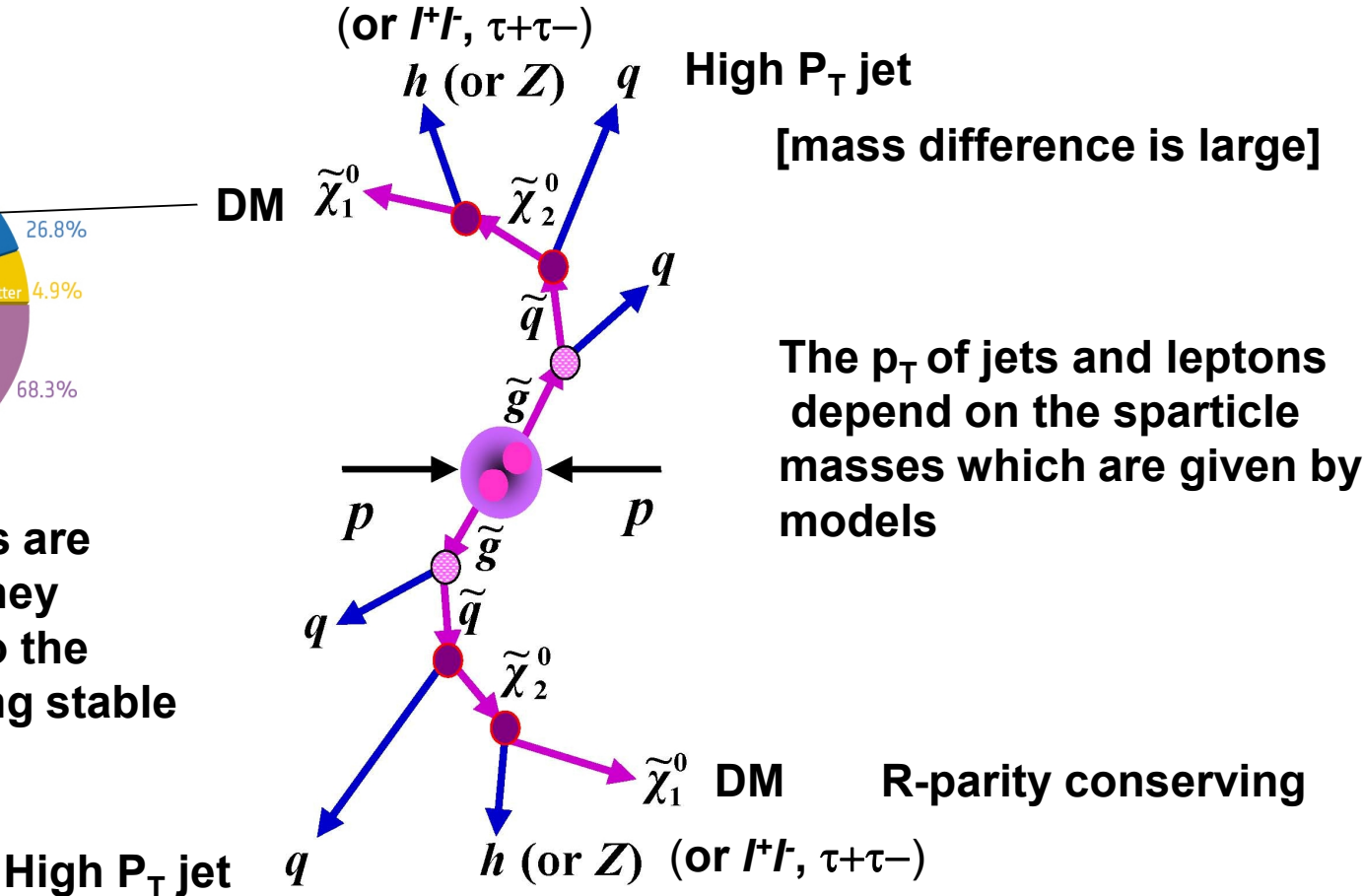
Small mass gaps between LSP and NLSP \rightarrow
coannihilation \rightarrow increase the annihilation cross-section



Small ΔM via cascade



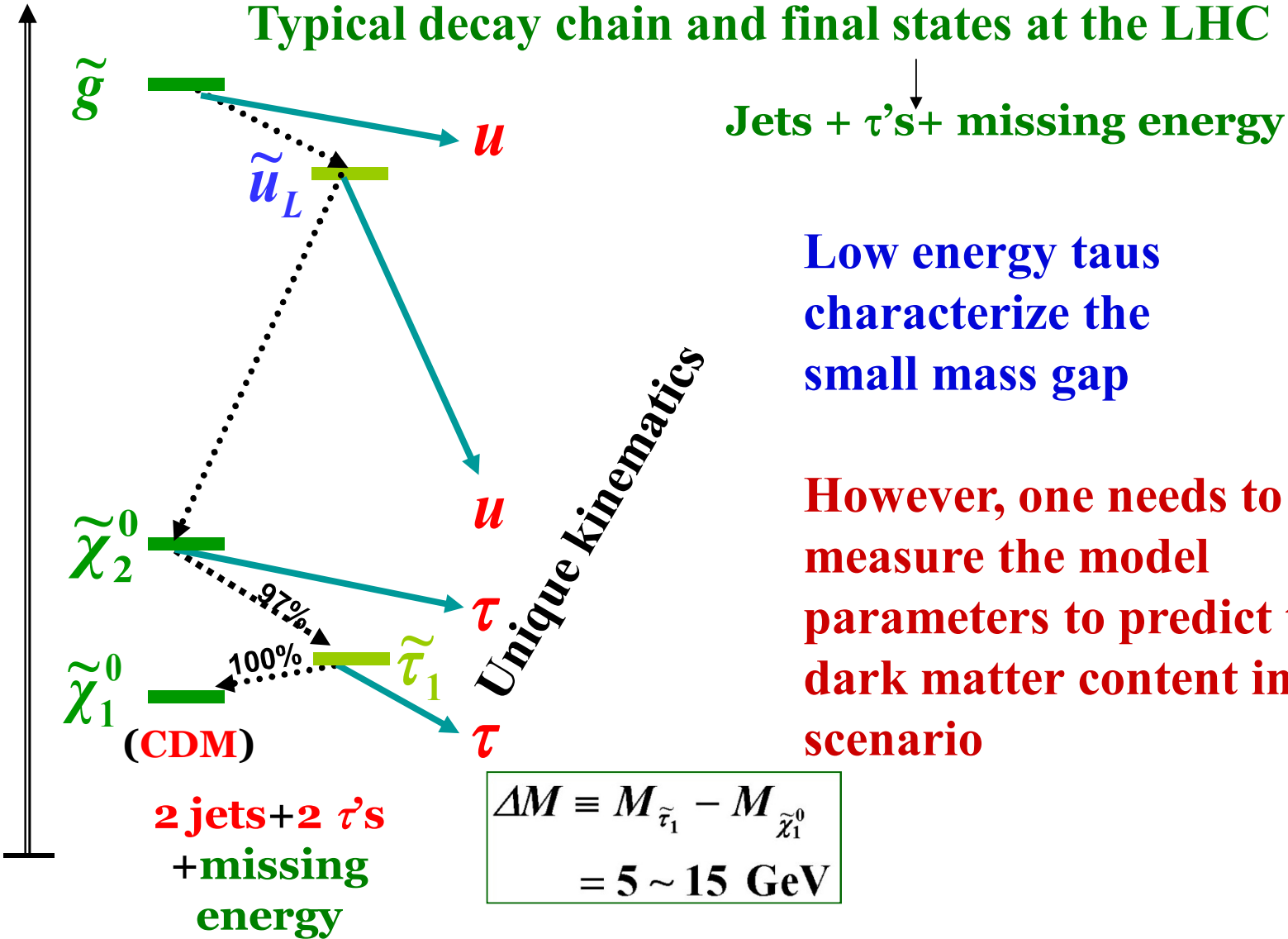
Colored particles are produced and they decay finally into the weakly interacting stable particle



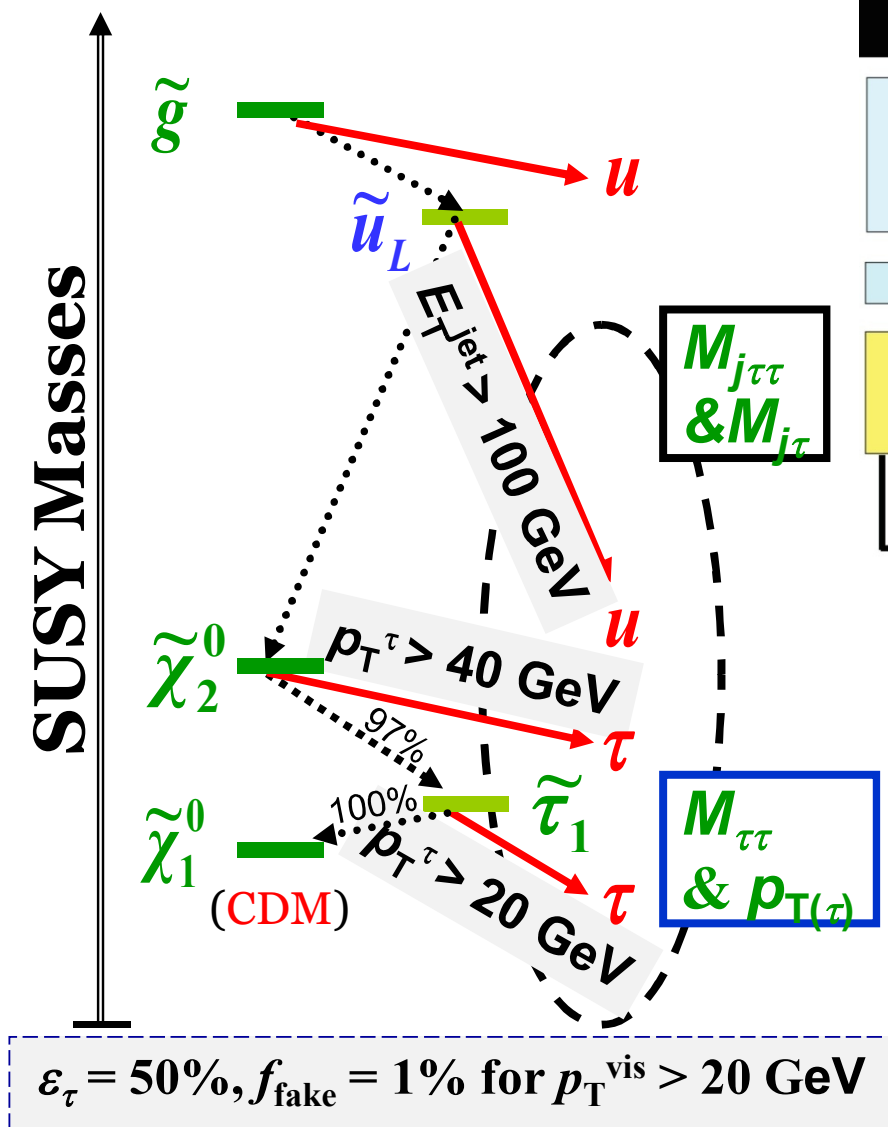
The signal :

jets + leptons + t's + W's + Z's + H's + missing E_T

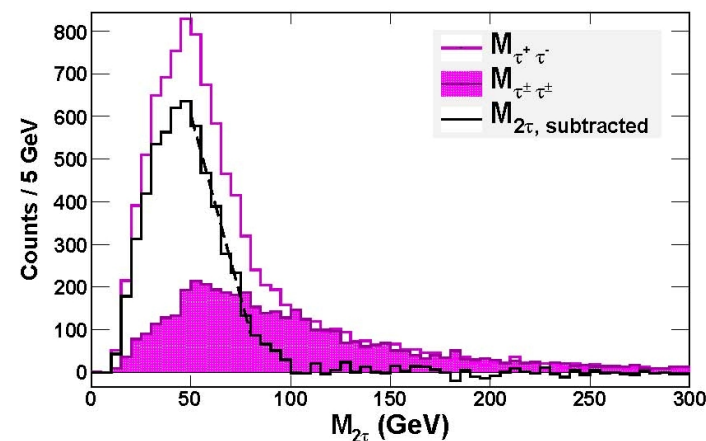
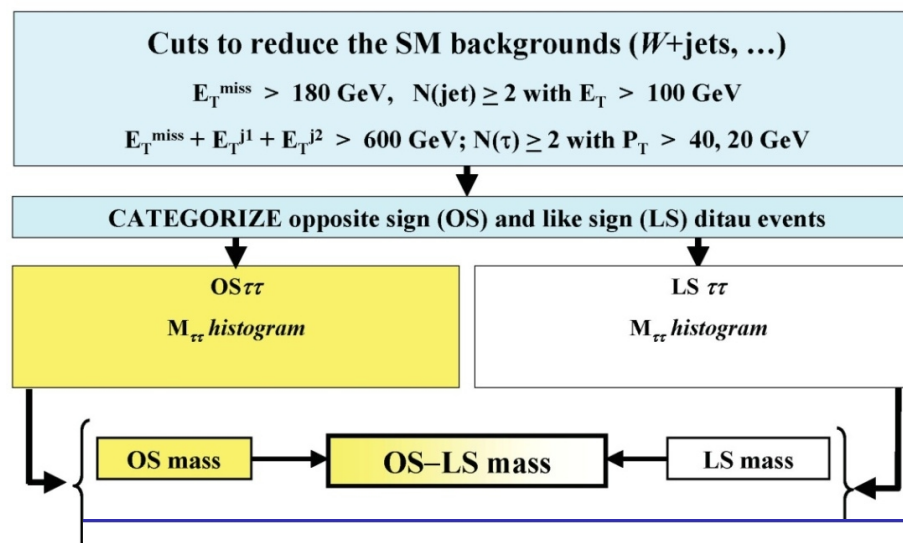
Small ΔM via cascade



Small ΔM via cascade



$E_T^{\text{miss}} + 2j + 2\tau$ Analysis Path



Arnowitz, Dutta, Gurrola, Kamon,
Krislock and Toback'PRL, 08

Small ΔM via cascade and DM

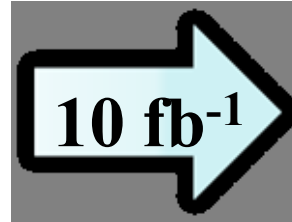
✓ Solved by inverting the following functions:

$$M_{j\tau\tau}^{\text{peak}} = X_1(m_{1/2}, m_0)$$

$$M_{\tau\tau}^{\text{peak}} = X_2(m_{1/2}, m_0, \tan \beta, A_0)$$

$$M_{\text{eff}}^{\text{peak}} = X_3(m_{1/2}, m_0)$$

$$M_{\text{eff}}^{(b)\text{peak}} = X_4(m_{1/2}, m_0, \tan \beta, A_0)$$

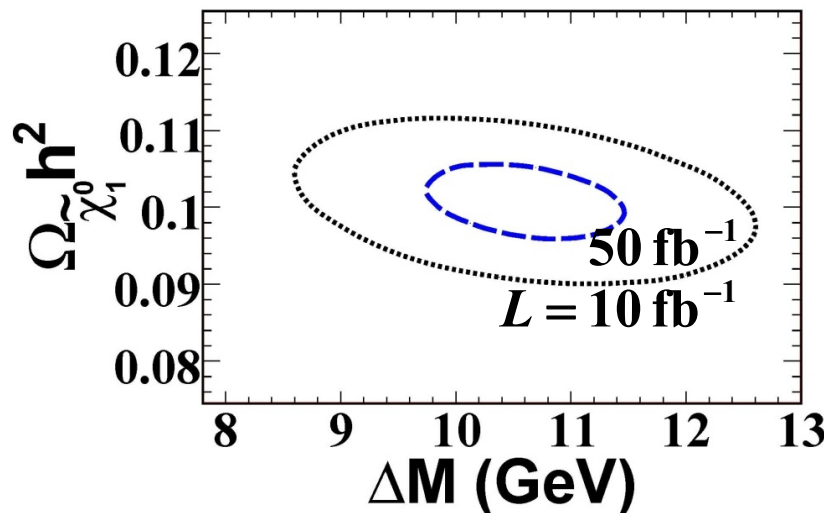


$$m_0 = 210 \pm 5$$

$$m_{1/2} = 350 \pm 4$$

$$A_0 = 0 \pm 16$$

$$\tan \beta = 40 \pm 1$$



$$\Omega_{\tilde{\chi}_1^0} h^2 = Z(m_0, m_{1/2}, \tan \beta, A_0)$$



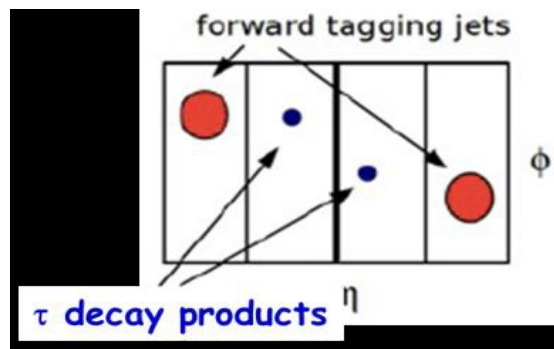
$$\begin{aligned} \delta \Omega_{\tilde{\chi}_1^0} h^2 / \Omega_{\tilde{\chi}_1^0} h^2 &= 6.2\% (30 \text{ fb}^{-1}) \\ &= 4.1\% (70 \text{ fb}^{-1}) \end{aligned}$$

Small ΔM via VBF

Challenge:

How can we probe the colorless SUSY sector if the first two generations are heavy?

We will use VBF topology: Tagging VBF jets



Refs (For example):

A. Datta, P. Konar, and B. Mukhopadhyaya, PRL 88 (2002) 181802.

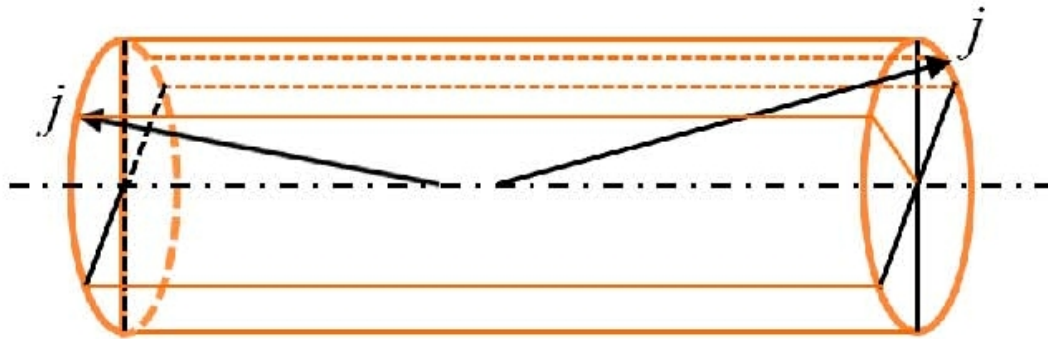
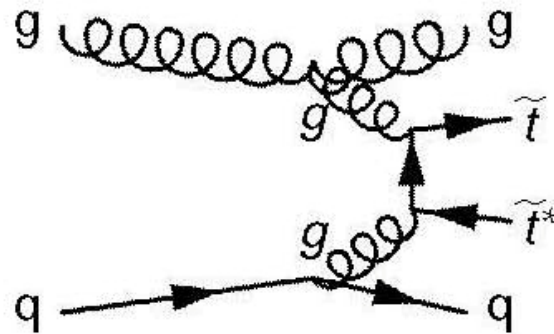
G. Giudice, T. Han, K. Wang, and L.T. Wang, PRD 87 (2013) 035029

Dutta, Gurrola, Kamon, John, Sinha, Sheldon; Phys.Rev. D87 (2013) 035029

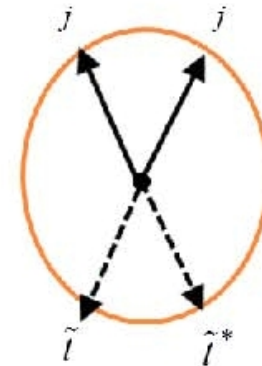
A.G. Delannoy, B. Dutta, A. Gurrola, W. Johns, T. Kamon, E. Luiggi, A. Melo,

P. Sheldon, K. Sinha, K. Wang, S. Wu, PRL 111 (2013) 061801

VBF For small ΔM



VBF tagged jets (2 energetic jets with large $\Delta\eta$ separation: large $M(jj)$ in forward region, opposite hemispheres)

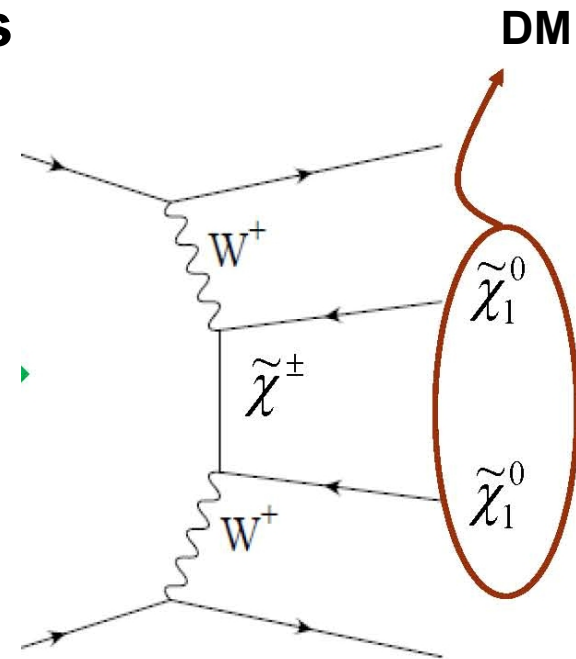
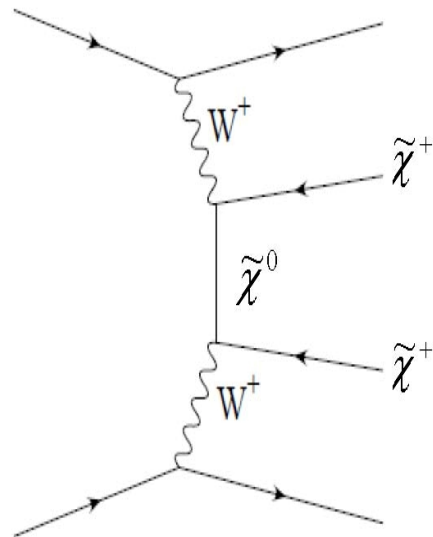


VBF production topology in transverse plane

Compressed SUSY Via VBF

- Direct probes of charginos, neutralinos and sleptons:
Do not have strong limits from the LHC (depends on Δm)
- The weak Bosons from protons can produce them
We need special search strategies

$P + P \rightarrow$



Two high E_T forward jets in opposite hemispheres with large dijet invariant mass

Compressed SUSY Via VBF

$$pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\pm jj, \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp jj, \tilde{\chi}_1^\pm \tilde{\chi}_2^0 jj, \tilde{\chi}_2^0 \tilde{\chi}_2^0 jj$$

For : $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^0} > m_{\tilde{l}} > m_{\tilde{\chi}_1^0}$

Signal: $\geq 2j + 2\tau + \text{missing energy}, \quad \geq 2j + 2\mu + \text{missing energy}$

→ Small mass (Δm) difference between chargino and neutralino

Dutta, Gurrola, Kamon, John, Sinha, Shledon; Phys.Rev. D87 (2013) 035029

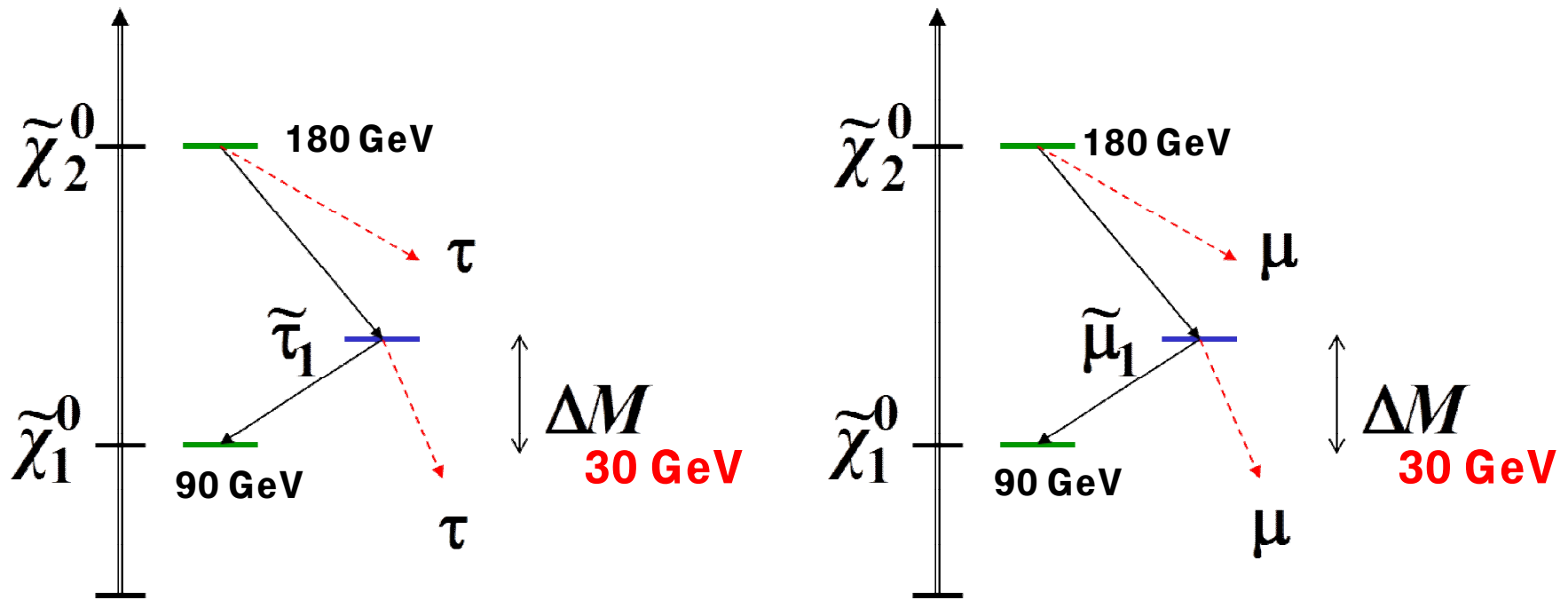
Charginos, Neutralinos via VBF

2 jets with $p_T(j) > 50 \text{ GeV}$; $p_T(j_1) > 75 \text{ GeV}$

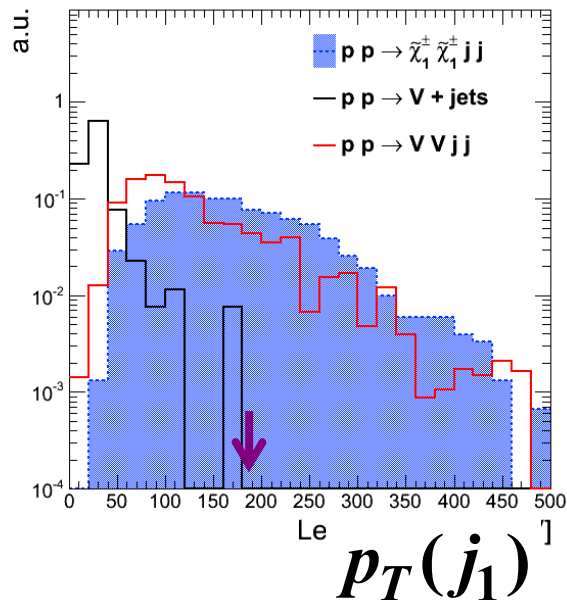
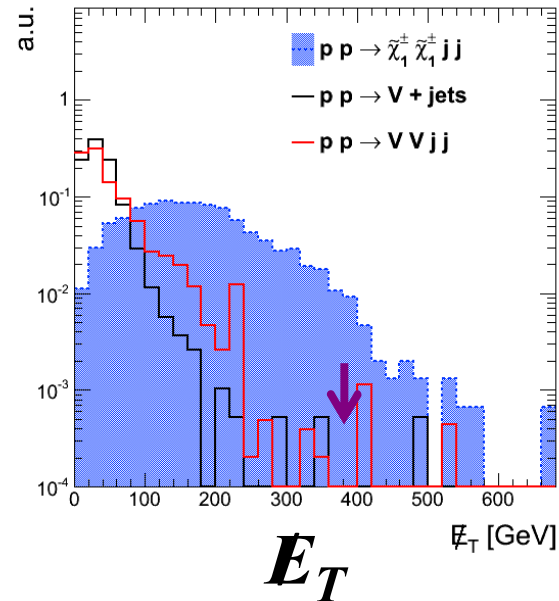
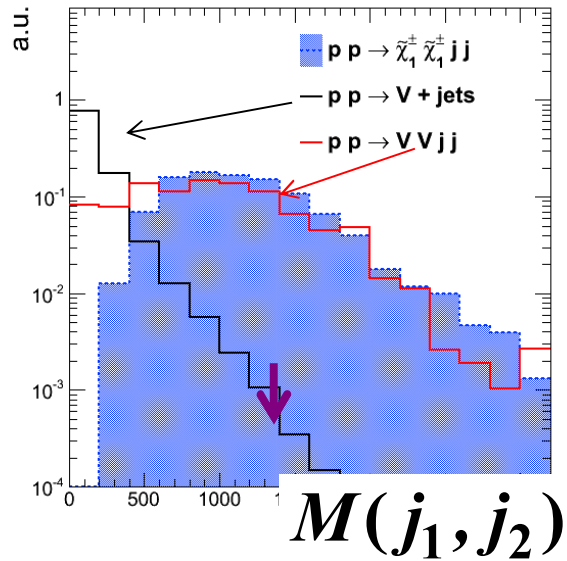
$|\Delta\eta| > 4.2$; $\eta_1 \cdot \eta_2 < 0$

$M(j_1, j_2) > 650 \text{ GeV}$; $\text{MET} > 75 \text{ GeV}$

2 Benchmark Scenarios



VBF Kinematics



$$M(\tilde{\chi}_1^+) \sim M(\tilde{\chi}_2^0) = 180 \text{ GeV}$$

$$M(\tilde{\chi}_1^0) = 90 \text{ GeV}$$

$$M(\tilde{\tau}_1^+) - M(\tilde{\chi}_1^0) = 30 \text{ GeV}$$

Signal Characteristics:
Large MET, large M_{jj} , large p_T jets

Phys. Rev. D 87, 035029 (2013)

Signal: $\geq 2j+2\tau$ +missing energy

2 jets each with $p_T > 50$ GeV, leading $p_T > 75$ GeV
 $|\Delta\eta(j_1, j_2)| > 4.2$, $\eta_{j_1} \eta_{j_2} < 0$, $M_{j_1 j_2} > 650$ GeV

Signal: $\geq 2j + 2\tau +$ missing energy

$$m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} = 180 \text{ GeV},$$

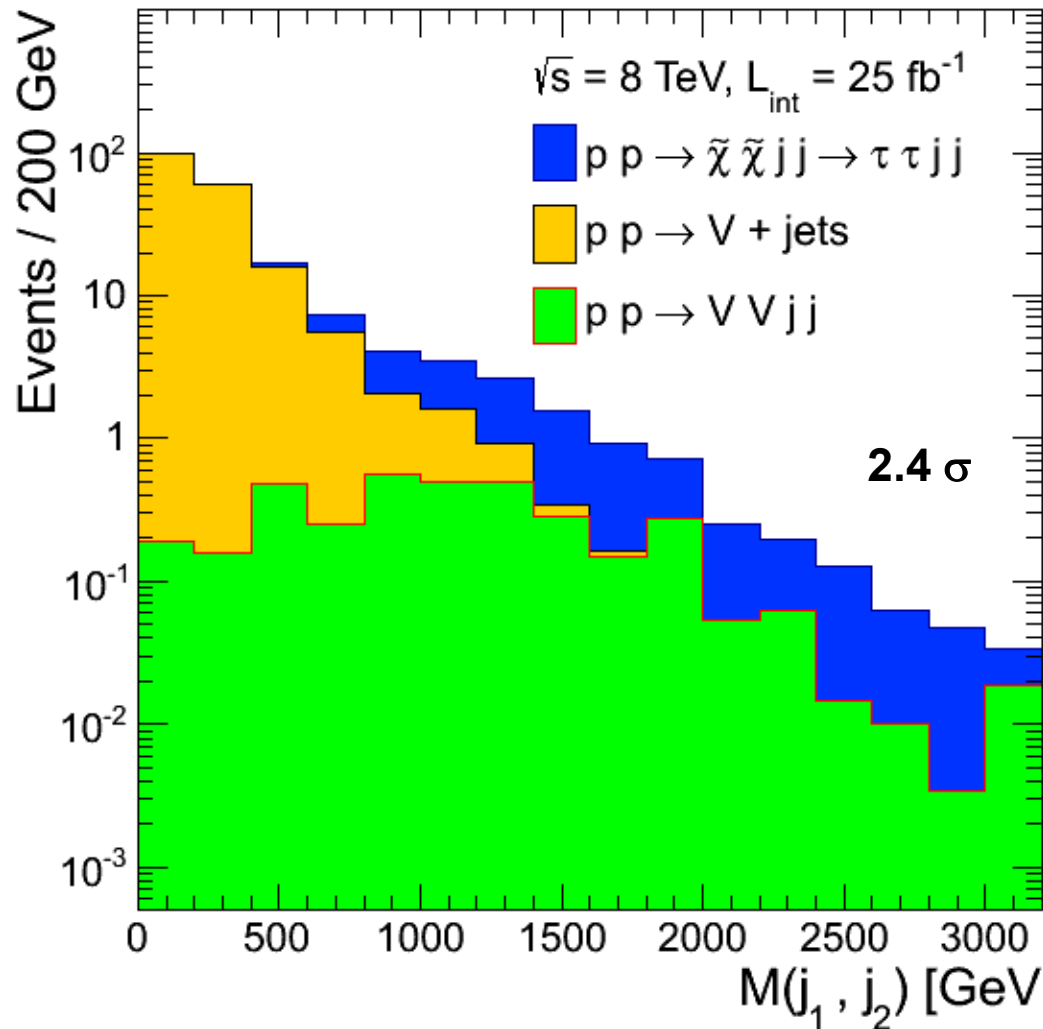
$$\sqrt{s} = 8 \text{ TeV}$$

Lum: 25 fb^{-1}

	Signal	Z+jets	W+jets	WW	WZ
VBF cuts	4.61	10.9	3.70×10^3	97.0	19.0
$\cancel{E}_T > 75, b\text{-veto}$	4.33	0.27	5.29×10^2	17.6	3.45
2τ , inclusive	0.45	0.06	0.23	0.09	0.04
$(S/\sqrt{S+B})$			2.4		
$\tau^\pm \tau^\pm$	0.21	0	0.11	0.02	0.01
$(S/\sqrt{S+B})$			1.8		
$\tau^\pm \tau^\mp$	0.24	0.06	0.12	0.07	0.03
$(S/\sqrt{S+B})$			1.7		

Two τ 's with $p_T > 20$ GeV in $\eta < 2.1$, with $\Delta R(\tau\tau) > 0.3$. All τ 's are hadronic
 The τ ID efficiency is assumed to be 55% and the jet $\rightarrow\tau$ Mis-identification rate is taken to be 1%,

Signal: $\geq 2j+2\tau$ +missing energy



Signal: $\geq 2j+2\mu$ +missing energy

2 jets each with $p_T > 50$ GeV, leading $p_T > 75$ GeV
 $|\Delta\eta(j_1, j_2)| > 4.2$, $\eta_{j_1} \eta_{j_2} < 0$, $M_{j_1 j_2} > 650$ GeV

Signal: $\geq 2j + 2\mu$ + missing energy $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} = 180$ GeV,

	Signal	Z+jets	W+jets	WW	WZ
VBF cuts	4.61	10.9	3.70×10^3	97.0	19.0
$\cancel{E}_T > 75$	4.33	0.27	5.29×10^2	17.6	3.45
2μ , inclusive	1.83	0.15	0	0.12	0.19
$(S/\sqrt{S+B})$			6.0		
$\mu^\pm \mu^\pm$	0.87	0	0	0.03	0.05
$(S/\sqrt{S+B})$			4.5		
$\mu^\pm \mu^\mp$	0.96	0.15	0	0.09	0.14
$(S/\sqrt{S+B})$			4.1		

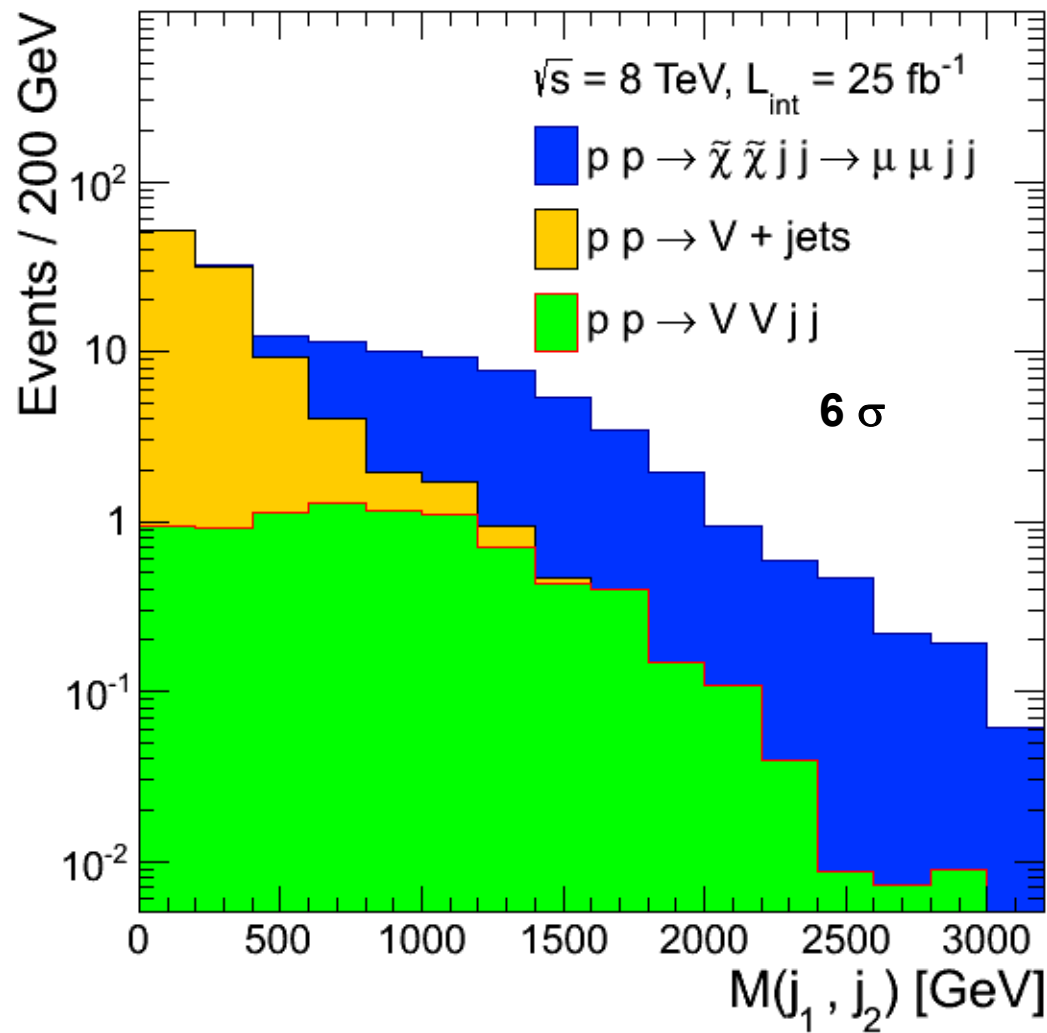
$\sqrt{s} = 8$ TeV

Lum: 25 fb⁻¹

Two isolated μ 's with $p_T > 20$ GeV in $\eta < 2.1$

For 3σ : $m_{\tilde{\chi}_1^\pm} \sim m_{\tilde{\chi}_2^0} = 330$ GeV

Signal: $\geq 2j+2\mu$ +missing energy



Compressed Sleptons Via VBF

Small mass gap measurements using VBF topology →

Various Coannihilation regions:

$$\tilde{\mu}, \tilde{e} - \tilde{\chi}_1^0, \tilde{\tau} - \tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\chi}_2^0 - \tilde{\chi}_1^0, \tilde{t} - \tilde{\chi}_1^0, \hat{b} - \tilde{\chi}_1^0$$

$$pp \rightarrow \tilde{\mu}\tilde{\mu}jj \quad \text{Signal: } 2j + 2\mu + \text{ missing energy,}$$

$$pp \rightarrow \tilde{\nu}\tilde{\mu}jj \quad \text{Signal: } 2j + 1\mu + \text{ missing energy,}$$

$$\Delta m = m_{\tilde{\mu}} - m_{\tilde{\chi}_1^0} = 15 \text{ GeV}$$

Compressed Sleptons Via VBF

cuts	mul135_chi120	tbar+(0-3) j	vv jj
loose MG cuts	0.4910	6931.00	1341.0000
Iso cuts&Mjj Mmumu >= 0.	0.4910	6931.00	1341.0000
veto b jets	0.4801	1583.28	1231.1200
# of Jets>=1 with pt>=30	0.4607	1437.39	1224.5800
# of Jets>=2 with pt>=30	0.3429	949.43	1170.4700
# of Jets = 2	0.2653	520.66	207.5180
etaj0*etaj1 <= 0.	0.2473	185.12	157.5180
# of Muons >= 2	0.0761	96.25	7.2801
# of Muons = 2	0.0761	95.87	6.8183
OS di-muon	0.0761	95.70	5.3751
N(electron)=0	0.0761	94.56	4.8779
N(tau) = 0	0.0746	80.00	4.4326
veto Mmumu 81~101	0.0679	69.03	2.5363
central muon selection	0.0514	28.89	1.8934
etaj >= 1.7	0.0257	3.66	0.9333
Mjj >= 600.	0.0247	2.01	0.8964
central jet veto	0.0247	2.01	0.8964
DeltaPhiij < 1.0	0.0096	0.49	0.1195
MissingET >= 200.	0.0039	0.01	0.0155
HT >= 200.	0.0039	0.01	0.0131
ptmu1+ptmu2<70	0.0024	0.00	0.0029
ptmu1 > 5 & ptmu2 > 5	0.0024		0.0029
ptmu1 > 10 & ptmu2 >5	0.0024		0.0029
ptmu1 >10 & ptmu2 >10	0.0021		0.0029

Typical Backgrounds

Combining
 $\tilde{\mu}\tilde{\mu}jj, \tilde{\mu}\tilde{\nu}jj$

LHC 14 TeV data): Signal: $2j + \geq 1\mu + \text{missing energy}$,
3 σ reach is 150 GeV for 3000 fb⁻¹

Dutta, Ghosh, Gurrola, Kamon, Sinha, Wang, Wu; to appear

Stop at the LHC

Utilize Stop decay modes to search charginos, sleptons, neutralinos

Ex. 1 χ_1^0 is mostly bino and χ_2^0 is wino

$$\tilde{t}_1 \rightarrow t + \tilde{\chi}_1^0$$

Stop can identified via fully hadronic or 1 lepton plus multijet final states

[Bai, Cheng, Gallichio, Gu, JHEP 1207 (2012) 110
;Han, Katz, Krohn, Reece, JHEP 1208 (2012)
083;Plehn, Spannowsky, Takeuchi, JHEP 1208
(2012) 091;Kaplan, Rehermann, Stolarski, JHEP
1207 (2012) 119; Dutta, Kamon, Kolev, Sinha, Wang,
Phys.Rev. D86 (2012) 075004]

Ex. 2 $\chi_{1,2}^0$ are mostly Higgsino

Topness variable to identify stops

Grasser, Shelton, Phys.Rev.Lett. 111 (2013) 121802

Ex. 3 χ_1^0 is mostly Bino-Higgsino
Correct relic density

For lighter sleptons

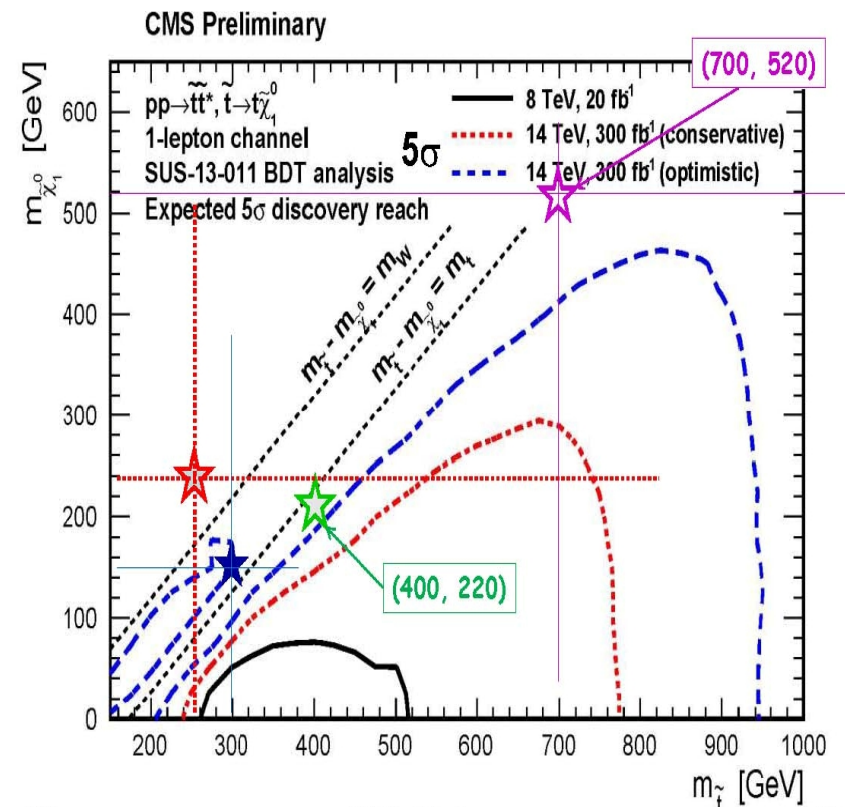
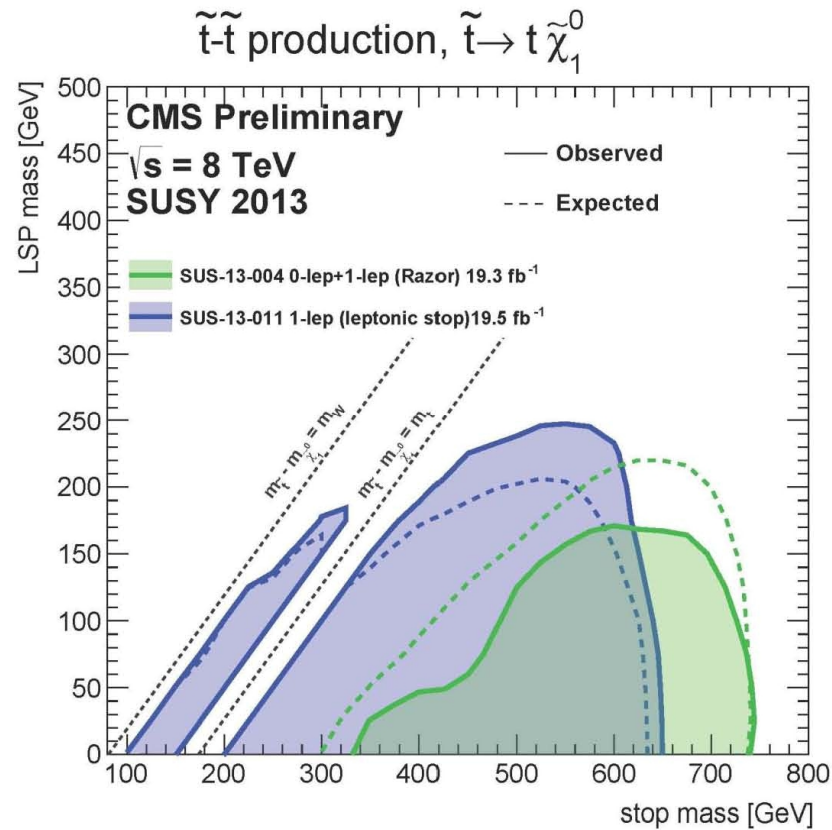
$$\begin{aligned}\tilde{t}_1 &\rightarrow t + \tilde{\chi}_2^0 \rightarrow t + l + \tilde{l}^* \rightarrow t + l + \bar{l} + \tilde{\chi}_1^0, \\ \tilde{t}_1 &\rightarrow b + \tilde{\chi}_1^\pm \rightarrow t + \nu + \tilde{l} \rightarrow t + l + \nu + \tilde{\chi}_1^0 \\ \tilde{t}_1 &\rightarrow t + \tilde{\chi}_1^0\end{aligned}$$

2 jets+ 2 leptons (OSSF-OSDF)
+missing energy

Dutta, Kamon, Kolev,Wang, Wu,
Phys. Rev. D 87, 095007 (2013)

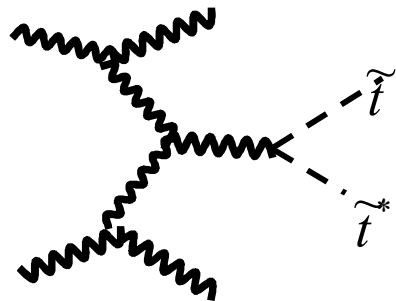
→ Existence and type of DM particle, hard to calculate the DM content

Compressed Stop Via VBF



Small ΔM have cosmological consequences

Compressed Stop Via VBF

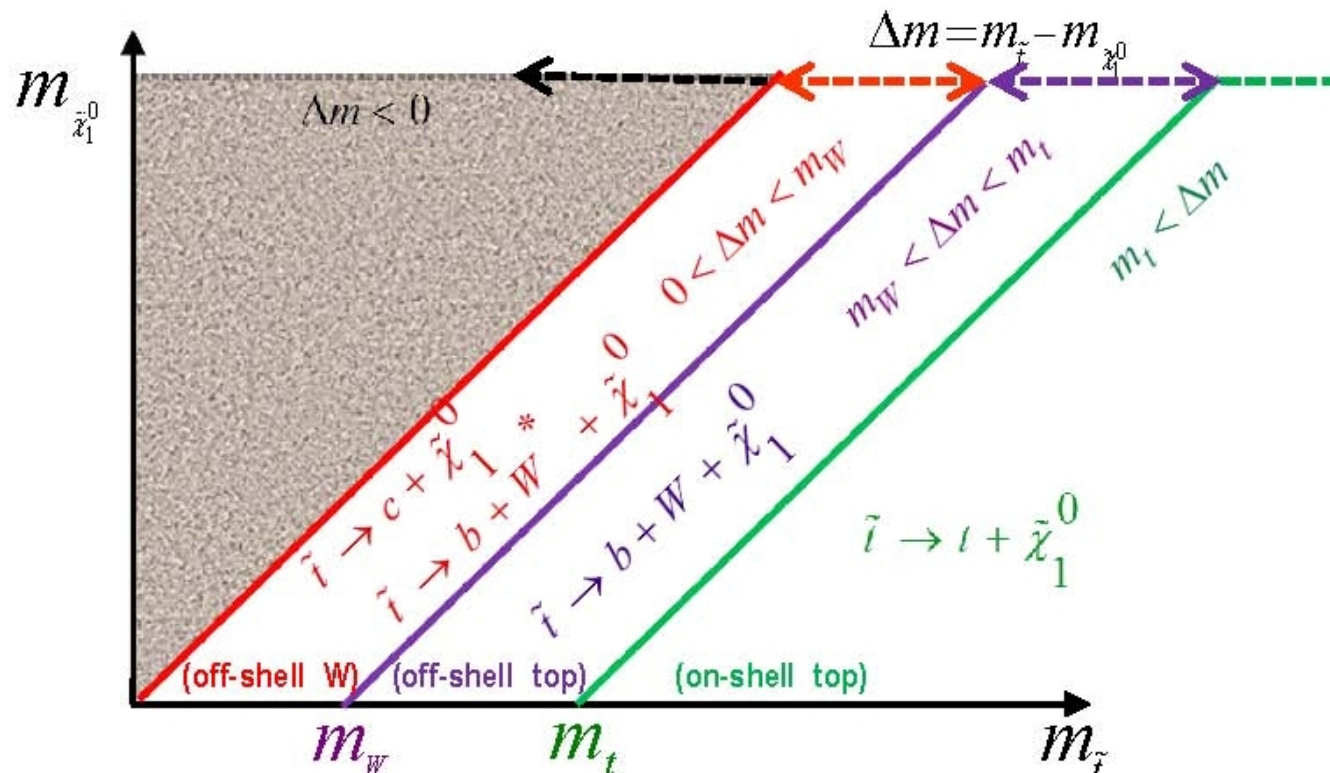


Signal: 2 j + 2 b + 1 l + missing energy

Compressed Region: $\Delta M \equiv m_{\tilde{t}} - m_{\tilde{\chi}_1^0} = 180, 165 \text{ GeV}$

$$\Delta M < m_t : \tilde{t} \rightarrow b + W + \tilde{\chi}_1^0$$

$$\Delta M > m_t : \tilde{t} \rightarrow t + \tilde{\chi}_1^0$$



Compressed Stop Via VBF

**2 leading jets (j_1, j_2) : $p_T(j_1, j_2) > (75, 50)$ GeV ,
 $|\Delta\eta(j_1, j_2)| > 3.5$ and $\eta_{j_1}\eta_{j_2} < 0$, $M_{j_1 j_2} > 500$ GeV; MET is optimized
 One isolated lepton ($p_T > 20$), two loose b jets ($p_T > 30$) : $\eta < 2.5$**

$$\Delta M > m_t : \tilde{t} \rightarrow t + \tilde{\chi}_1^0$$

TABLE I: Compressed scenario: Summary of the effective cross-sections (fb) for different benchmark signal points as well as the $t\bar{t}$ background at LHC14. Masses and momenta are in GeV.

$(m_{\tilde{t}}, m_{\tilde{\chi}_1^0})$	Selection	Signal	$t\bar{t}$ +jets
(300, 120)	VBF	95.7	16774
	1 lepton	22.1	3587
	2 b -jets	9.70	1612
	$\cancel{E}_T > 50$	8.00	924
(400, 220)	VBF	25.2	16774
	1 lepton	5.93	3587
	2 b -jets	2.84	1612
	$\cancel{E}_T > 100$	1.48	337
(500, 320)	VBF	7.50	16774
	1 lepton	1.69	3587
	2 b -jets	0.74	1612
	$\cancel{E}_T > 150$	0.27	123

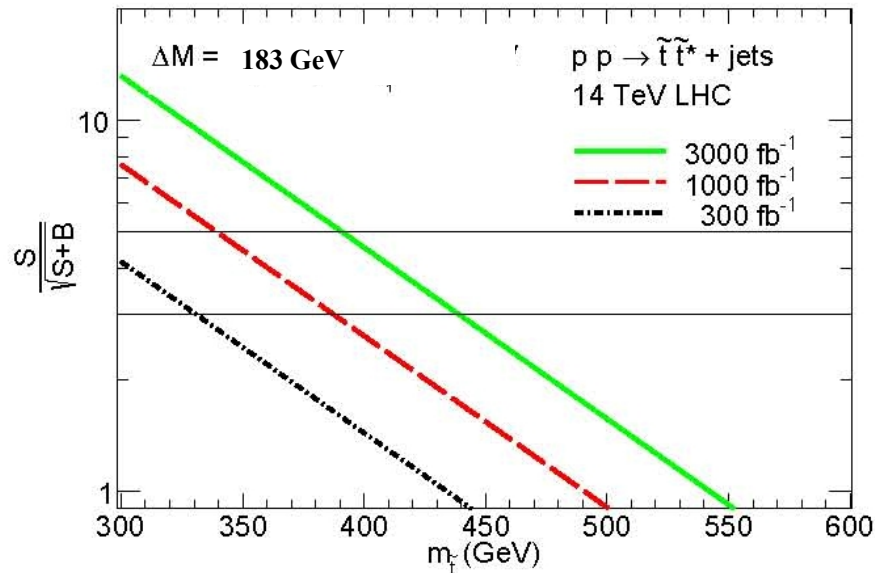
$$\Delta M < m_t : \tilde{t} \rightarrow b + W + \tilde{\chi}_1^0$$

TABLE II: Summary of the effective cross-sections (fb) for different benchmark signal points as well as the $t\bar{t}$ background at LHC14. Masses and momenta are in GeV.

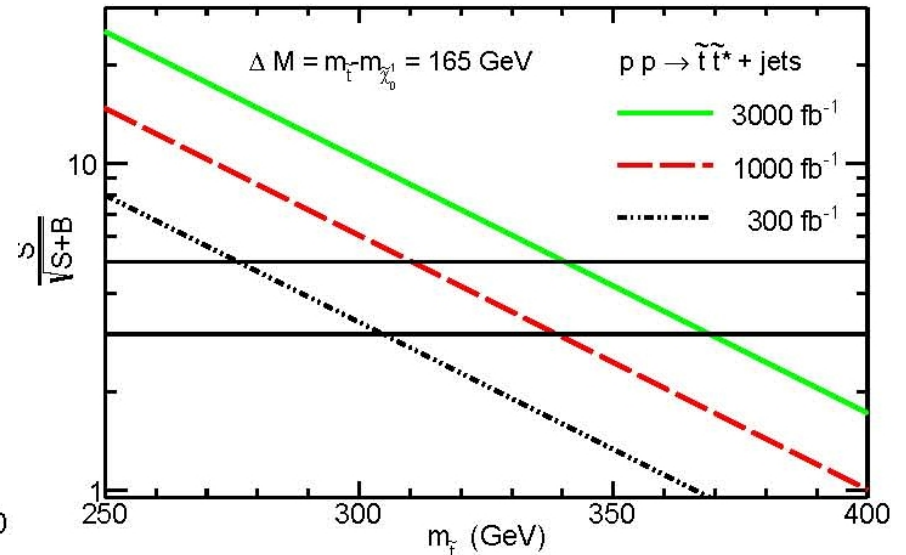
$(m_{\tilde{t}}, m_{\tilde{\chi}_1^0})$	Selection	Signal	$t\bar{t}$ +jets
(250, 85) $\Delta M = 165$ GeV	VBF	465.6	38787.8
	1 lepton	93.5	8107.9
	2 b -jets	25.3	3096
	$\cancel{E}_T > 100$	12.9	682.5
(300, 135) $\Delta M = 165$ GeV	VBF	217.9	38387.8
	1 lepton	42.8	8107.9
	2 b -jets	11.5	3096
	$\cancel{E}_T > 100$	6.7	682.5
(400, 235) $\Delta M = 165$ GeV	VBF	50.6	38387.8
	1 lepton	10.3	8107.9
	2 b -jets	2.76	3096
	$\cancel{E}_T > 200$	1.92	682.5
(300, 150) $\Delta M = 150$ GeV	VBF	194.2	38387.8
	1 lepton	39.9	8107.9
	2 b -jets	8.09	3096
	$\cancel{E}_T > 100$	5.00	682.5

Compressed Stop Via VBF

$$\Delta M > m_t : \tilde{t} \rightarrow t + \tilde{\chi}_1^0$$



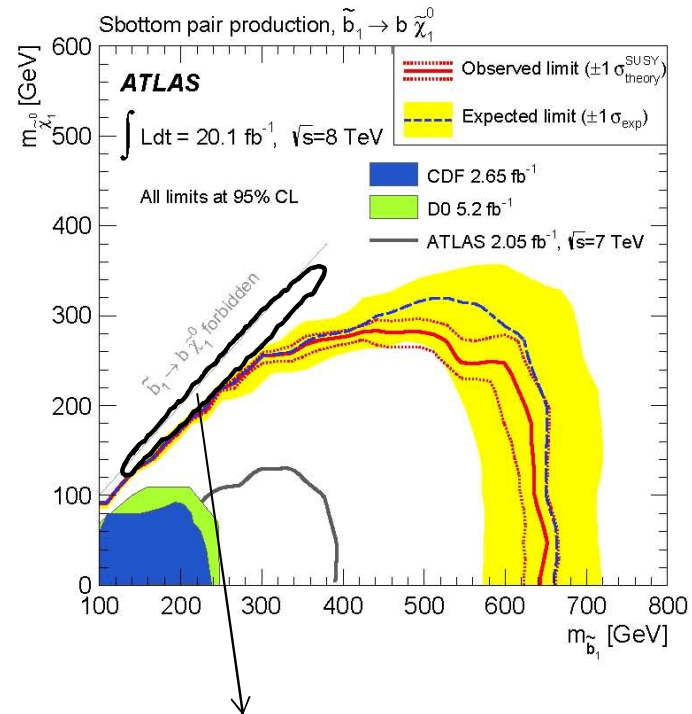
$$\Delta M < m_t : \tilde{t} \rightarrow b + W + \tilde{\chi}_1^0$$



The significance reduces to 3σ with 3% sys . for 200 GeV stop

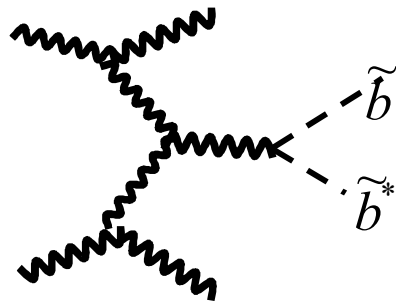
Dutta, Flanagan, Gurrola, Kamon, Sheldon, Sinha, Wang, Wu; 1312.1348

Compressed Sbottom



We probe this region

Compressed Sbottom Via VBF



Signal: 2 j + 1 b + missing energy

Compressed Region: $\Delta M \equiv m_{\tilde{b}} - m_{\chi_1^0} = 5 \text{ GeV}$

Dutta, Gurrola, Kamon, Sinha, Wang, S. Wu, Z. Wu; to appear

Signal: 2 j + 1 b + missing energy:

(Delphes, 140 pileup): 300 GeV with 3σ (5% syst. @ 3000 fb⁻¹)
[similar reach for 300 fb⁻¹ with 0 pileup]

Signal: 2 j + missing energy:

(Delphes, 140 pileup): 300 GeV with 3σ (5% syst. @ 3000 fb⁻¹)

Compressed Sbottom Via VBF

Significance vs mass with systematics (Preliminary)

VBF + MET + B @ 0PU

Background: 655 with 300/fb

Mass	XS(pb)	Eff.	S/B	$\frac{S}{\sqrt{S+B}}$	5% Sys.	10% Sys.
15	704.190002	0.62	2015.71	1148.75	1148.29	1146.89
50	74.722855	0.57	196.78	358.10	356.63	352.32
100	11.100344	0.29	15.00	95.96	91.40	80.83
150	2.699331	0.54	6.68	61.67	55.99	45.30
200	0.905649	0.22	0.91	16.89	12.39	8.03
300	0.158608	0.27	0.20	4.67	3.04	1.84
400	0.040765	0.32	0.06	1.51	0.95	0.56
500	0.012975	0.21	0.01	0.32	0.20	0.12
600	0.004798	0.21	0.00	0.12	0.07	0.04
700	0.001958	0.26	0.00	0.06	0.04	0.02
1000	0.000194	0.20	0.00	0.00	0.00	0.00

- $H_T - E_T$ asymmetry cut: $|H_T - E_T|/(H_T + E_T) < 0.2$ for 0 pileup, 0.5 for 140 pileup interactions
 - protect against occasional loss of high p_T jets due to pileup subtraction
- VBF selection: (Using non b -tag jets for VBF jets and central jet veto)
 - $H_T > 50\text{GeV}$
 - $p_T^{\text{jet1,2}} > 50\text{GeV}$
 - $|\eta^{\text{jet1,2}}| < 5$
 - $|\eta^{\text{jet1}} - \eta^{\text{jet2}}| > 4.2$
 - $\eta^{\text{jet1}} \cdot \eta^{\text{jet2}} < 0$
- $p_T^{\text{jet1}} > 50\text{GeV}$ (200GeV when studying 140 pileup scenarios)
- $p_T^{\text{jet2}} > 50\text{GeV}$ (100GeV when studying 140 pileup scenarios)
- $M_{jj} > 1500\text{GeV}$
- Veto a third jet with $p_T^{\text{jet3}} > 30\text{GeV}$ lying between leading two jets
- Veto a lepton (electron, muon, and tau)
- $H_T > 200\text{GeV}$
- Exactly one a b -tagged jet
- PT of this b -tagged jet $< 80\text{GeV}$

VBF + MET

Total BK: 34165 with 300/fb

Mass(GeV)	XS(pb)	Eff.	S/B	$\frac{S}{\sqrt{S+B}}$	5% Sys.	10% Sys.
15	704.190002	0.04	2.47	245.30	48.49	24.61
50	74.722855	4.27	28.04	961.82	484.50	269.22
100	11.100344	8.50	8.29	502.69	157.44	81.78
150	2.699331	12.99	3.08	281.76	60.15	30.60
200	0.905649	14.46	1.15	144.96	22.71	11.46
300	0.158608	19.92	0.28	45.37	5.51	2.77
400	0.040765	22.86	0.08	14.54	1.63	0.82
500	0.012975	24.24	0.03	5.03	0.55	0.28
600	0.004798	25.11	0.01	1.95	0.21	0.11
700	0.001958	26.61	0.00	0.84	0.09	0.05
1000	0.000194	27.72	0.00	0.09	0.01	0.00

- $H_T - E_T$ asymmetry cut: $|H_T - E_T|/(H_T + E_T) < 0.2$ for 0 pileup, 0.5 for 140 pileup interactions
 - protect against occasional loss of high p_T jets due to pileup subtraction
- VBF selection:
 - $H_T > 50\text{GeV}$
 - $p_T^{\text{jet1,2}} > 50\text{GeV}$
 - $|\eta^{\text{jet1,2}}| < 5$
 - $|\eta^{\text{jet1}} - \eta^{\text{jet2}}| > 4.2$
 - $\eta^{\text{jet1}} \cdot \eta^{\text{jet2}} < 0$
- $p_T^{\text{jet1}} > 50\text{GeV}$ (200GeV when studying 140 pileup scenarios)
- $p_T^{\text{jet2}} > 50\text{GeV}$ (100GeV when studying 140 pileup scenarios)
- $M_{jj} > 1500\text{GeV}$
- Veto a third jet with $p_T^{\text{jet3}} > 30\text{GeV}$ lying between leading two jets
- Veto a b -tagged jet
- Veto a lepton (electron, muon, and tau)
- $H_T > 200\text{GeV}$

Compressed Sbottom Via VBF

Significance vs mass with systematics with pile-up

VBF + MET @ 140PU

Total BK: 160123

Mass(GeV)	XS(pb)	Eff.	S/B	$\frac{S}{\sqrt{S+B}}$	5% Sys.	10% Sys.
15	704.190002	0.10	13.46	1416.24	264.41	133.97
50	74.722855	0.62	8.74	1120.32	172.63	87.09
100	11.100344	1.46	3.04	605.28	60.51	30.37
150	2.699331	2.54	1.28	339.88	25.60	12.83
200	0.905649	2.80	0.48	156.53	9.48	4.75
300	0.158608	4.50	0.13	50.28	2.67	1.34
400	0.040765	5.35	0.04	16.03	0.82	0.41
500	0.012975	5.80	0.01	5.60	0.28	0.14
600	0.004798	6.23	0.01	2.24	0.11	0.06
700	0.001958	6.59	0.00	0.97	0.05	0.02
1000	0.000194	6.99	0.00	0.10	0.01	0.00

Compressed Higgsino Via VBF

Lightest neutralino: Higgsino

$\tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{\chi}_2^0$: similar mass

We consider 10 GeV mass difference with final state

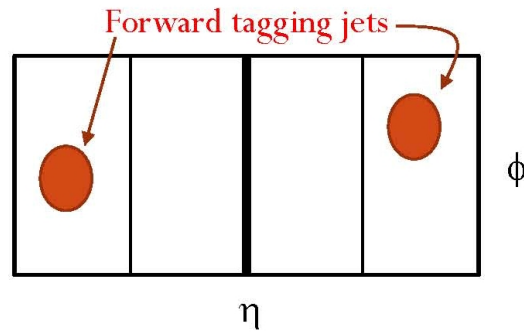
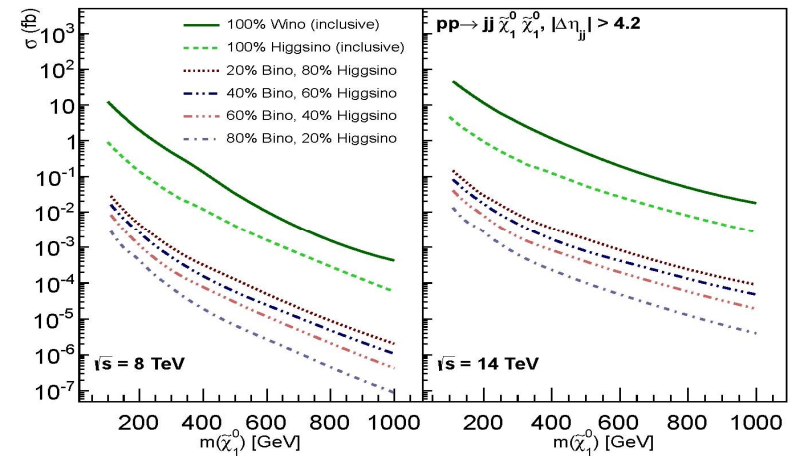
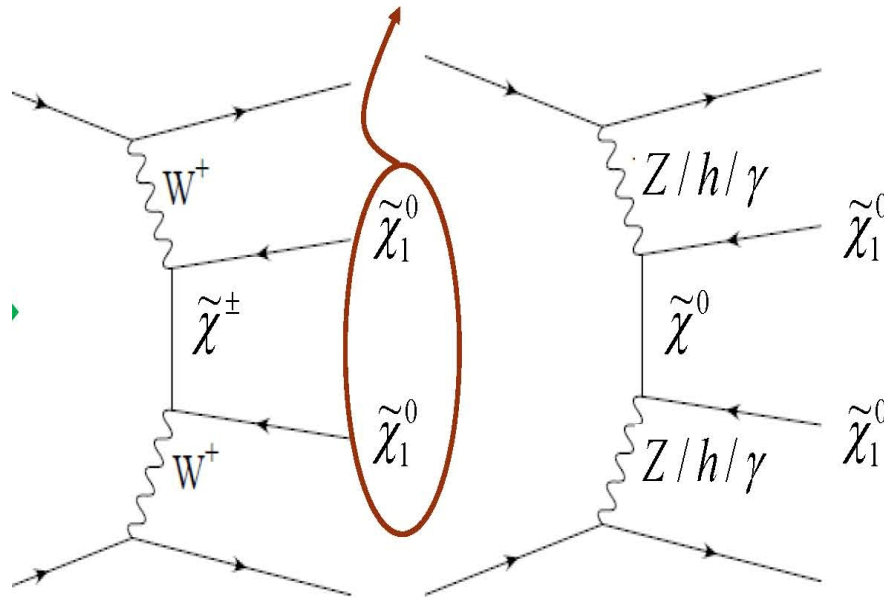
2 j+ Met + 1 lepton

**2 leading jets (j_1, j_2) : $p_T(j_1, j_2) > (75, 50)$ GeV ,
 $|\Delta\eta(j_1, j_2)| > 3.5$ and $\eta_{j_1}\eta_{j_2} < 0$, $M_{j_1 j_2} > 500$ GeV; MET is optimized
One isolated lepton ($p_T > 20$), two loose b jets ($p_T > 30$) : $\eta < 2.5$**

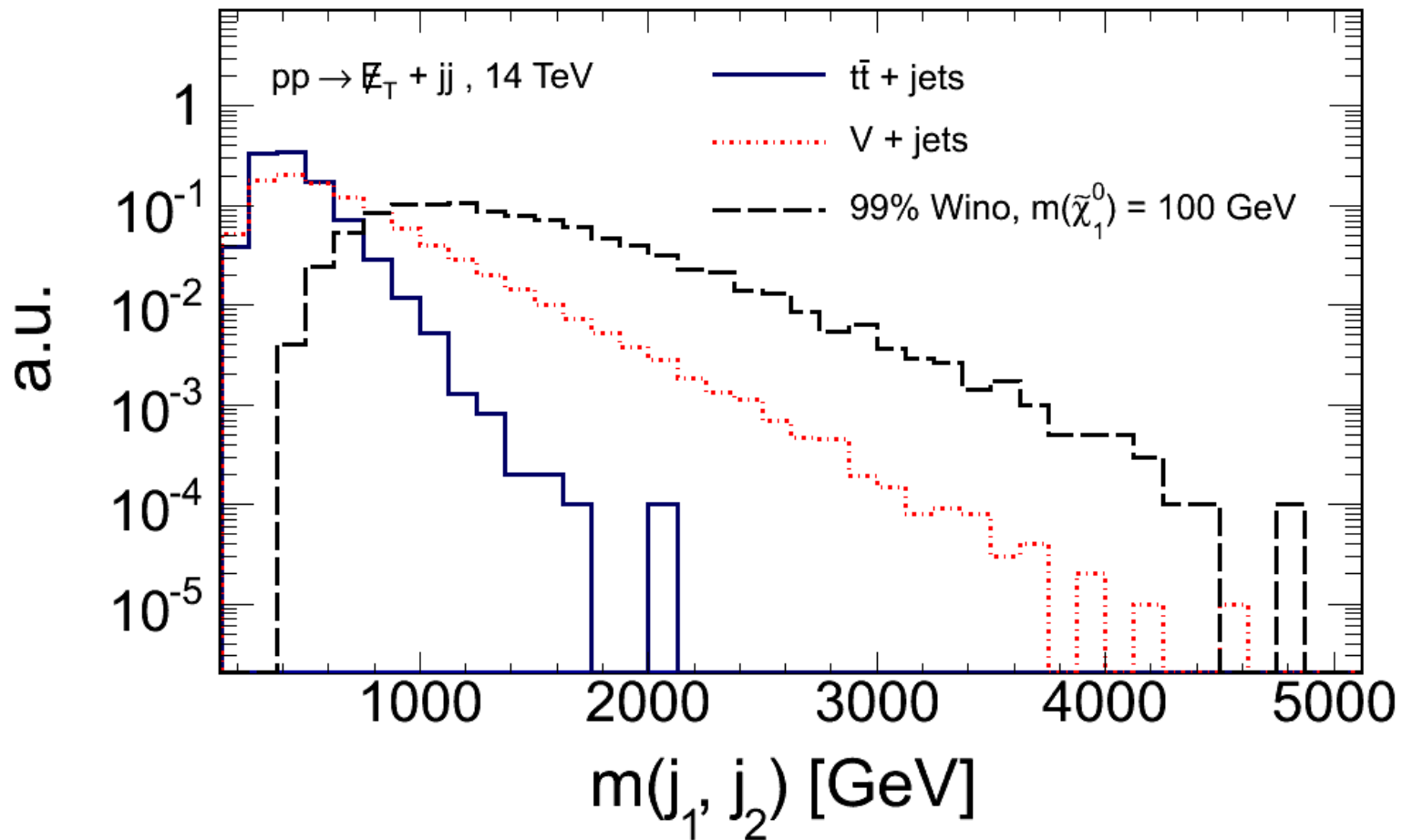
Compressed DM Via VBF

$$pp \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0 jj$$

CDM



Compressed DM Via VBF



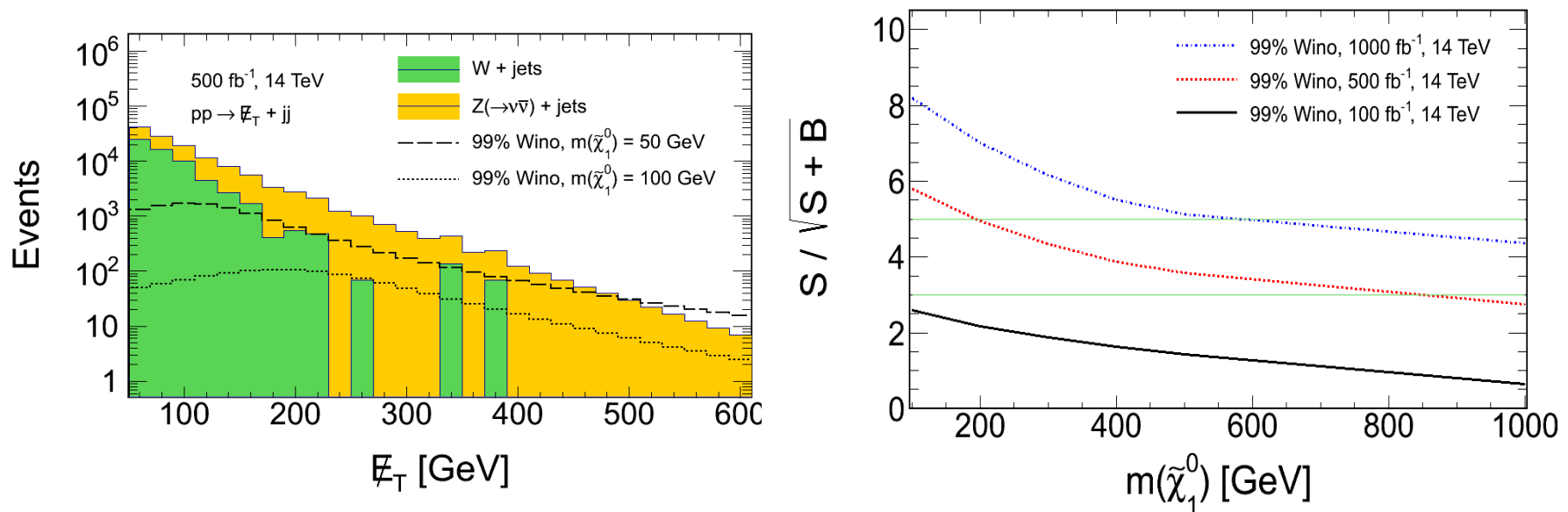
Compressed DM Via VBF

Preselection: missing $E_T > 50$ GeV, 2 leading jets (j_1, j_2) : $p_T(j_1), p_T(j_2) > 30$ GeV, $|\Delta\eta(j_1, j_2)| > 4.2$ and $\eta_{j1}\eta_{j2} < 0$.

Optimization: Tagged jets : $p_T > 50$ GeV, $M_{j1j2} > 1500$ GeV;

Events with leptons ($l = e; \mu; \tau_h$) and b-quark jets: rejected.

Missing E_T : optimized for different value of the LSP mass.

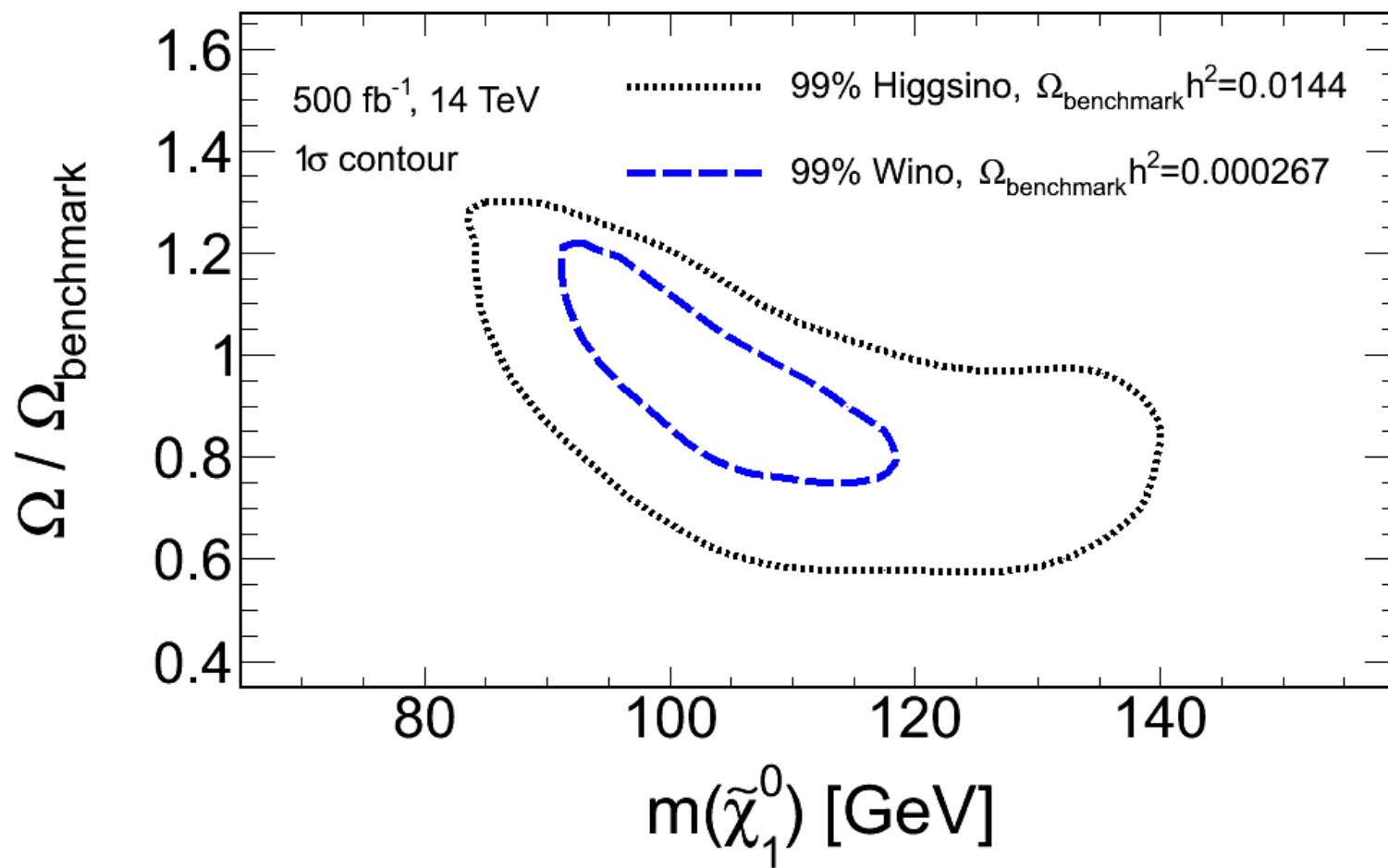


Jet energy scale uncertainty $\sim 20\%$ change the significance by 4%

Delannoy, Dutta, Kamon, Sinha, Wang, Wu et al; Phys.Rev.Lett. 111 (2013) 061801

Compressed DM Via VBF

Simultaneous fit of the observed rate,
shape of missing energy distribution:



Models with Double Charged Higgs Via VBF

$$L_Y = ih_{ij}^M \psi_{iL}^T C \tau_2 \Delta_L \psi_{jL} + cc$$

$$\Delta_L = \begin{pmatrix} \delta_L^+/\sqrt{2} & \delta_L^{++} \\ \delta_L^0 & -\delta_L^+/\sqrt{2} \end{pmatrix}$$

At the LHC:

$$PP \rightarrow \delta^{++} \delta^{--} jj, PP \rightarrow \delta^{\pm\pm} \delta^{\mp} jj$$

Two scenarios

$$1. BR(\delta_L \rightarrow \tau\tau) = 100\%$$

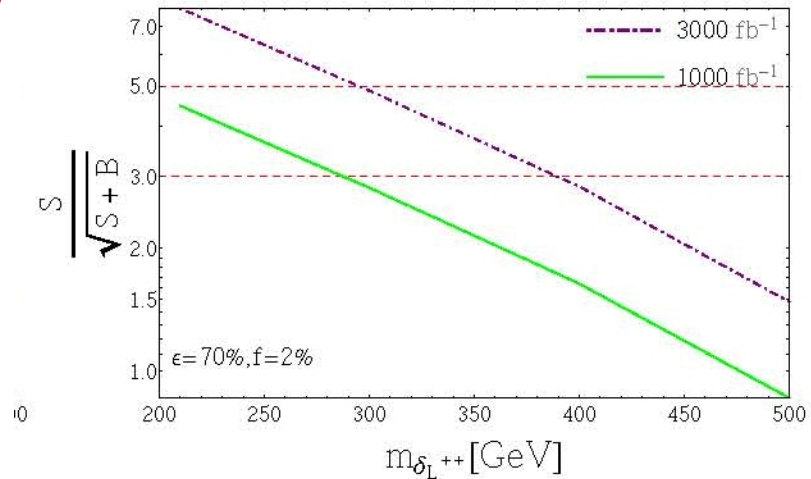
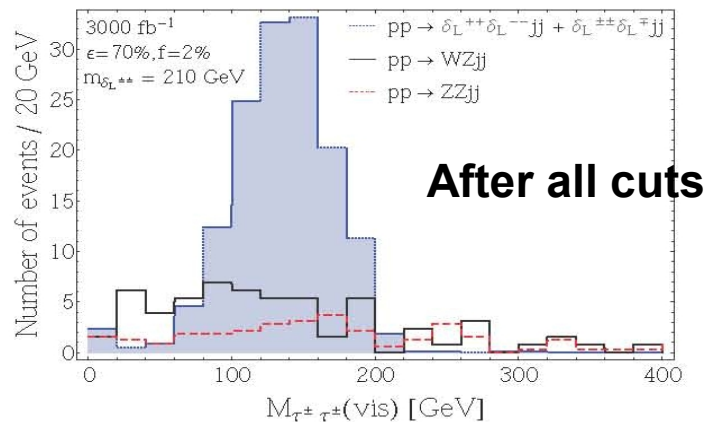
$$2. BR(\delta_L \rightarrow \mu\mu) = 50\%, BR(\delta_L \rightarrow ee) = 50\%$$

Double Charged Higgs Via VBF

$$1.BR(\delta_L \rightarrow \tau\tau) = 100\%$$

$(m_{\delta_L^{++}}, m_{\delta_L^+})$ [GeV]		Selection Cuts	Signal [fb]	ZZjj [fb]	WZjj [fb]
(210, 170)	$\epsilon = 50\%, f = 1\%$	Basic cuts	2.222 ± 0.009	585.9 ± 1.4	3513 ± 8
		VBF cuts	0.4655 ± 0.0040	39.98 ± 0.36	211.8 ± 2.1
		$\geq 3 \tau_h$'s	0.0196 ± 0.0008	0.0038 ± 0.0007	0.0138 ± 0.0028
	$\epsilon = 70\%, f = 2\%$	$\tau_h p_T$ cuts	0.0147 ± 0.0007	0.0016 ± 0.0005	0.0070 ± 0.0021
		\cancel{E}_T cut	0.0120 ± 0.0006	0.0011 ± 0.0004	0.0048 ± 0.0016
		$\geq 3 \tau_h$'s	0.0487 ± 0.0013	0.0068 ± 0.0009	0.0364 ± 0.0051
		$\tau_h p_T$ cuts	0.0356 ± 0.0006	0.0032 ± 0.0007	0.0168 ± 0.0034
		\cancel{E}_T cut	0.0292 ± 0.0010	0.0020 ± 0.0005	0.0112 ± 0.0027

2 leading jets (j_1, j_2) : $p_T(j_1, j_2) > (50, 50)$ GeV
 $|\Delta\eta(j_1, j_2)| > 4$ and $\eta_{j_1}\eta_{j_2} < 0$,
 $M_{j_1 j_2} > 500$ GeV; $MET > 50$ GeV
At least 3 τ_h with $p_T > 50, 50, 30$ GeV



Dutta, Eusebi, Ghosh, Gao, Kamon, 1404.0685

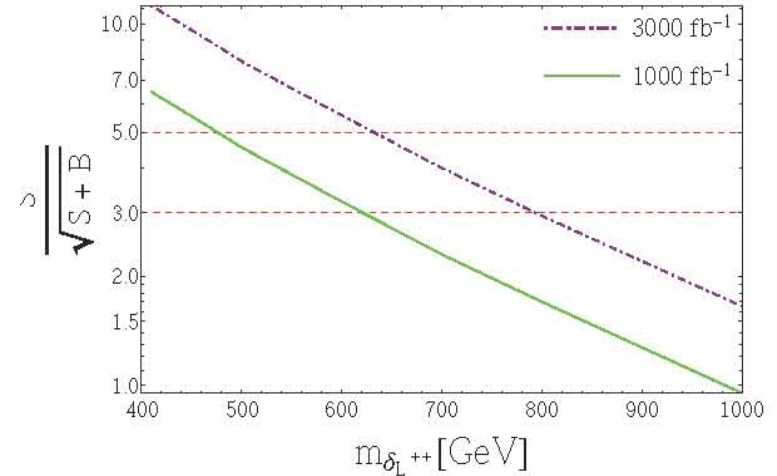
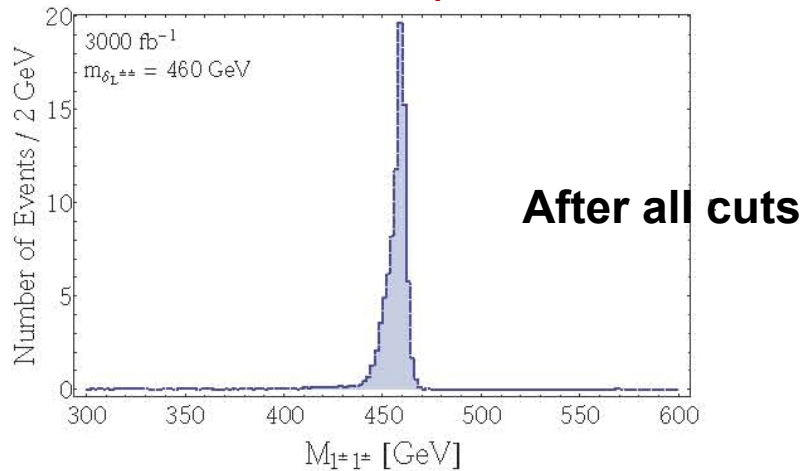
Double charged Higgs Via VBF

$$2.BR(\delta_L \rightarrow \mu\mu) = 50\%, BR(\delta_L \rightarrow ee) = 50\%$$

$(m_{\delta_L^{++}}, m_{\delta_L^+})$ [GeV]	Selection Cuts	Signal [fb]	ZZjj [fb]	WZjj [fb]
(460, 420)	Basic cuts	0.1540 ± 0.0011	585.9 ± 1.4	3513 ± 8
	VBF	0.0403 ± 0.0005	39.98 ± 0.36	211.8 ± 2.1
	≥ 3 leptons	0.0317 ± 0.0005	0.2131 ± 0.0028	1.702 ± 0.033
	lepton p_T cuts	0.0301 ± 0.0005	0.0126 ± 0.0007	0.1015 ± 0.0080
	Z-veto	0.0291 ± 0.0005	0.0005 ± 0.0001	0.0057 ± 0.0019
	δ_L^{++} mass window	0.0285 ± 0.0005	0.0001 ± 0.0001	0.0002 ± 0.0002

TABLE I. Summary of the signal and the background cross-sections and corresponding statistical errors at our chosen benchmark point, after each kinematical cut in the light lepton decay scenario. The LHC energy is 14 TeV.

**2 leading jets (j_1, j_2) : $p_T(j_1, j_2) > (50, 50)$ GeV ,
 $|\Delta\eta(j_1, j_2)| > 4$ and $\eta_{j_1}\eta_{j_2} < 0$,
 $M_{j_1 j_2} > 500$ GeV; MET > 50 GeV
 At least 3 leptons with $p_T > 120, 100, 50, 30$**



Conclusion

- **Measuring small mass gaps at the LHC is very important**
- **Small mass gaps between LSP and NLSP have cosmological consequences**
- **Small mass gaps can be measured from cascade decays of squarks, gluinos**
- **For heavier colored particles, VBF topology is very helpful in establishing signals with small mass gaps**

Back-up

